AFRL-RQ-WP-TM-2017-0017

SENSITIVITY ANALYSIS FOR MULTIDISCIPLINARY SYSTEMS (SAMS)

Richard D. Snyder
Design & Analysis Branch
Aerospace Vehicles Division

FEBRUARY 2017
Interim Report

AIR FORCE RESEARCH LABORATORY
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UNITED STATES AIR FORC

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14. ABSTRACT
The Sensitivity Analysis for Multidisciplinary Systems (SAMS) program aims to provide the aerospace community with reliable and robust tools for the economical and accurate evaluation of sensitivities for multidisciplinary design and analysis. The program is building on the well-known and widely-used FUN3D computational fluid dynamics solver, modularizing and expanding it to include adjoint-based aeroelastic sensitivities. The aeroelastic modeling will eventually support both mode-based structural representations and time-dependent, nonlinear finite element structural dynamics. This interim report describes progress towards the goals of the program.

15. SUBJECT TERMS
aeroelasticity, multidisciplinary analysis, multidisciplinary design, adjoint method, sensitivity analysis

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Sensitivity Analysis for Multidisciplinary Systems (SAMS)

Integrity ★ Service ★ Excellence

01 Dec 2016

Rich Snyder
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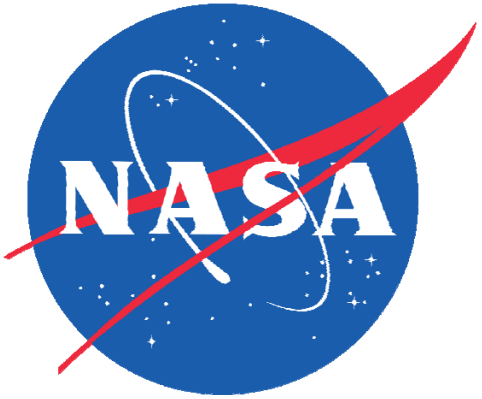
AFRL-NASA Collaboration

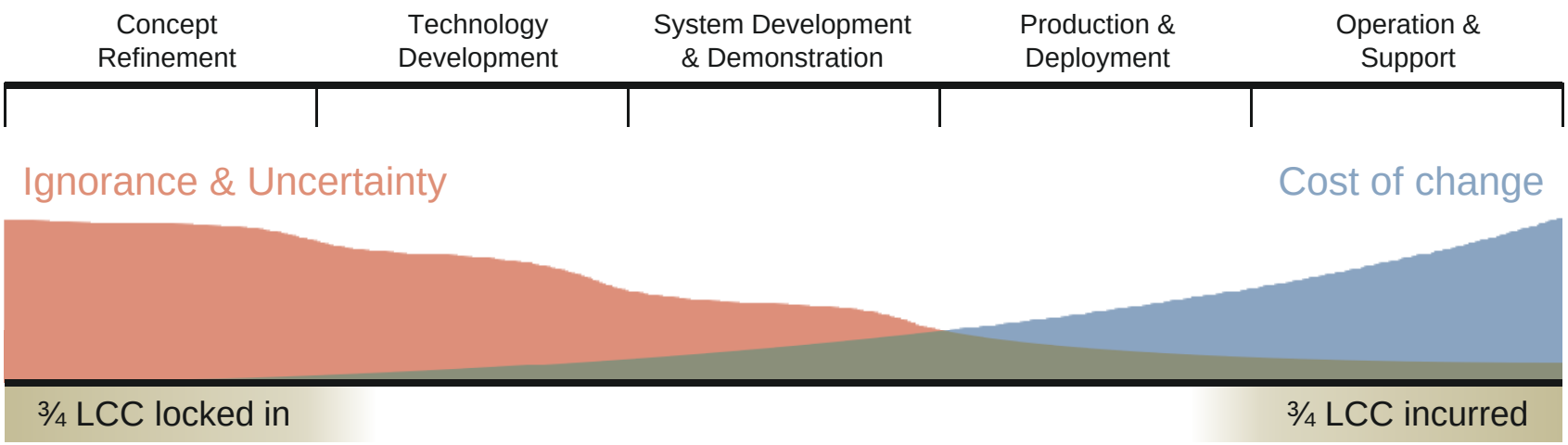
Provide
economical, accurate sensitivities
for multidisciplinary design
and analysis

Computational AeroSciences



SAMS Overview

Cost & Capability



- Knowledge is most limited when majority of cost is locked in
- Limited knowledge inevitably leads to mistakes

- Changes become more expensive over time
- Correcting/accepting mistakes means cost growth and/or lost capability

Better early modeling ⇒ Increased knowledge → informed decisions → Fewer mistakes ⇒ Successful design

Technology Impact

Candidate Technologies

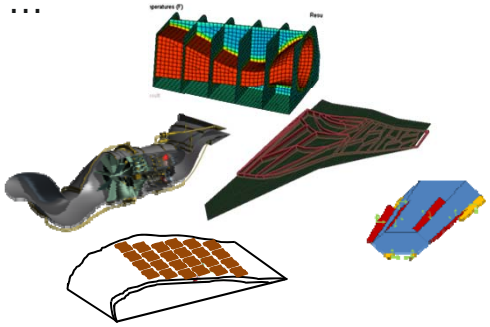
- Aeroelastic wing
- Flutter suppression
- Third stream engine
- Advanced materials
- Thrust vectoring
- Innovative control effectors
- Directed energy
- Conformal load bearing antennas
- …

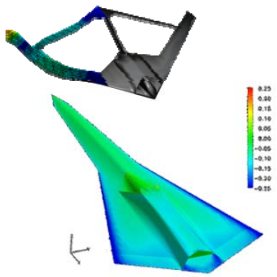
Engineering Capability

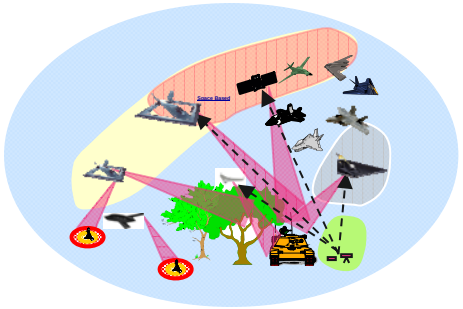
- Weight
- Drag
- Roll performance
- Yaw performance
- RCS
- Fuel efficiency
- Sensor efficiency
- …

Mission Capability

- Life cycle cost
- Survivability
- Maintainability
- Kills per $
- IDs per $
- …

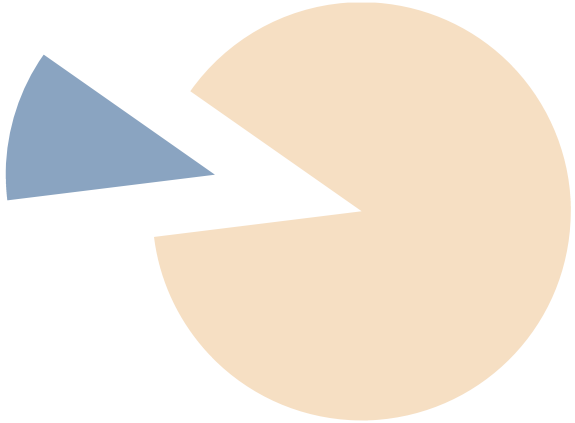






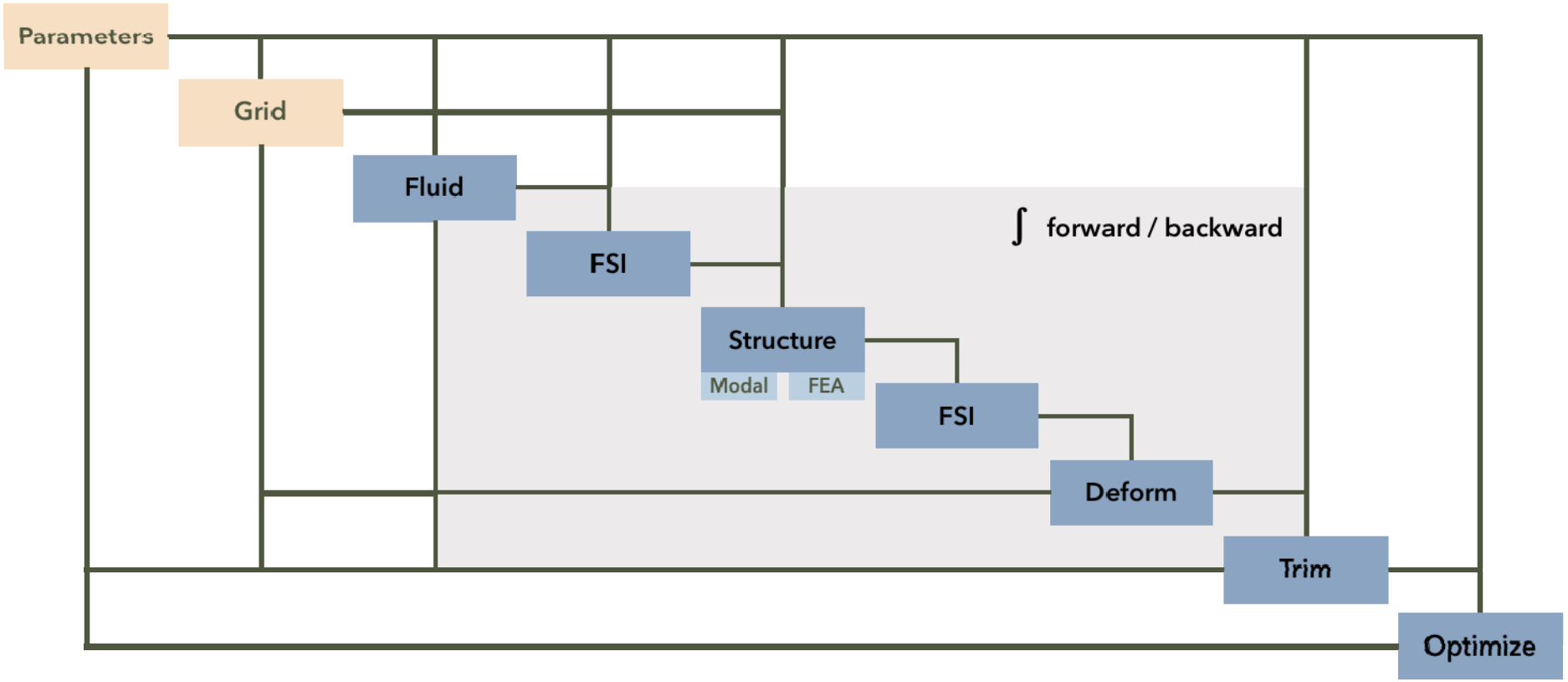
Use accurate physical models to obtain $\frac{\partial(\text{Mission Capability})}{\partial(\text{Technology})}$

Contribution



- CFD-based analytic aeroelastic sensitivities
- Steady and transient solutions
- Nonlinear structural dynamics
- Demonstrated capability
- Enhanced FUN3D

Components

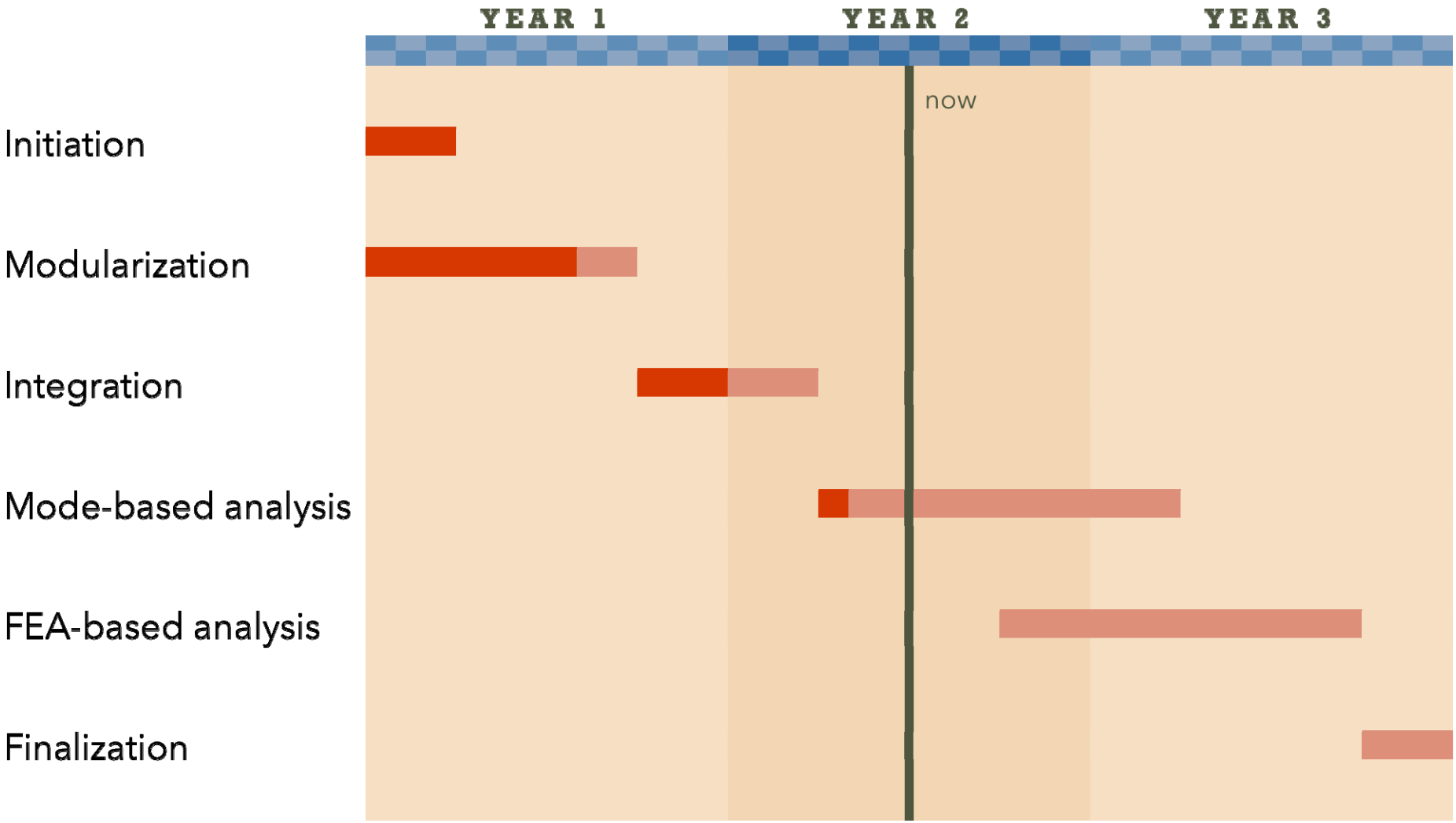


LEGEND

SAMS component

External component

Schedule


YEAR 1
YEAR 2
YEAR 3
now
Initiation
Modularization
Integration
Mode-based analysis
FEA-based analysis
Finalization

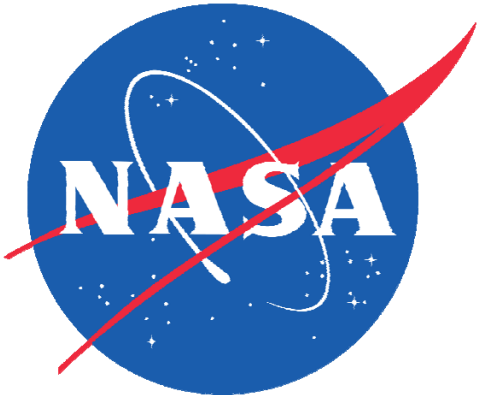
Current and Potential Customers

Government institutions

Academia

Aerospace companies

Other industries



Hermes
Integration Framework

Layered Networking

Components in a multidisciplinary simulation each have their own communication requirements, driving a layered networking model

MSTC Engineering ⋘or similar⋙

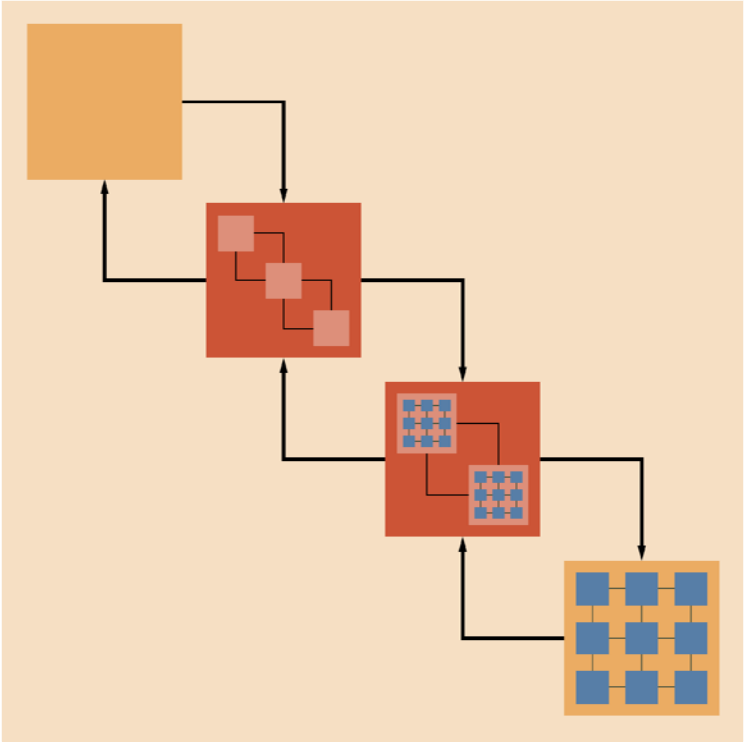
- MADO process model
- Geographically distributed components

Hermes ⋘built for SAMS⋙

- Fast coupling for unsteady analysis
- Locally distributed components

MPI

- Very fast coupling within a component
- Execution on a cluster/supercomputer



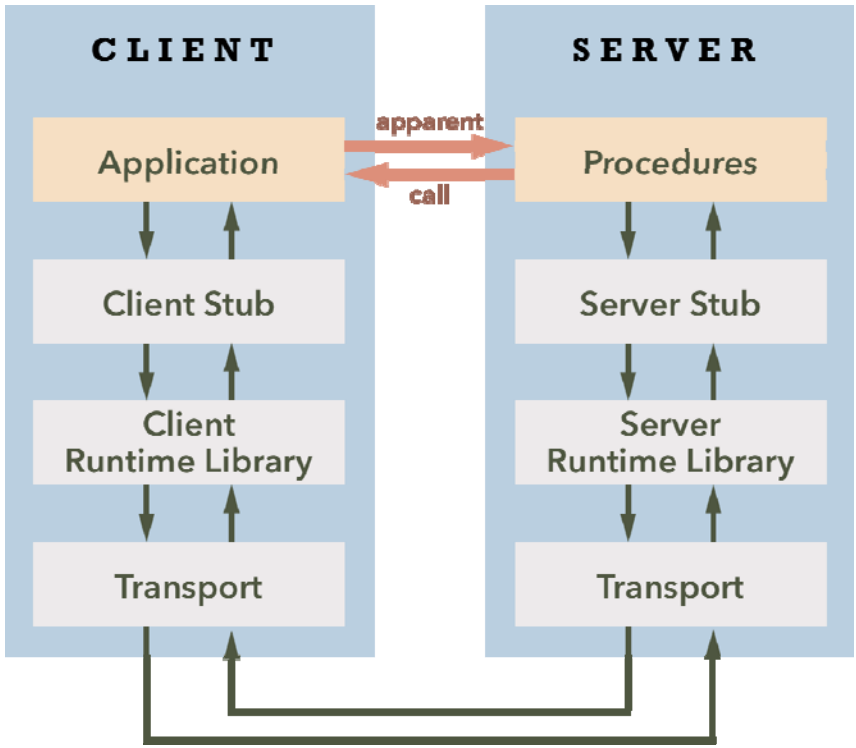
Notional N^2 diagram

Hermes Framework

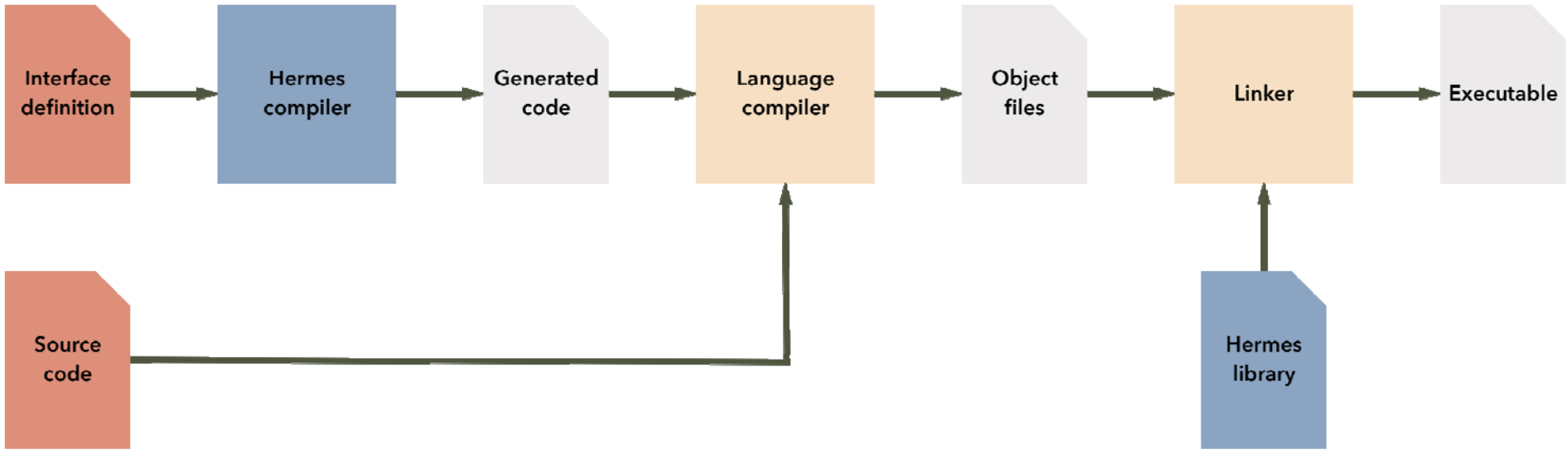
Characteristics

- Remote procedure calls
- Cross-language
  - C++
  - Fortran 2003
  - Python
  - …
- Built on ØMQ
  - Client-server communication
  - Message based
  - Several transport protocols
  - Several messaging patterns

Remote Procedure Call



Process



LEGEND

- Written by a developer
- Hermes components
- Other tools
- Generated files

Interface Definition


```
structure point {
  real64 x,
  real64 y
}

exception oops {
  int32 code
}

interface geometry {

  point centroid(vector<point> ps) throws (oops),
  real64 distance(point p, point q)

}
```

Defines a server's remotely callable procedures

Server and Client Code

Server

```
from geometry import Point, Geometry
import math
import zmq

class Server(Geometry.Server):
  def distance(self, p, q):
    dx = q.x – p.x
    dy = q.y – p.y
    return math.sqrt(dx * dx + dy * dy)
  def centroid(self, ps):
    x = sum([p.x for p in ps]) / len(ps)
    y = sum([p.y for p in ps]) / len(ps)
    return Point(x, y)

addr = 'tcp://*:49152'
ctx  = zmq.Context()
srv  = Server(ctx, addr, zmq.REP)
srv.serve()
srv.close()
ctx.destroy()
```

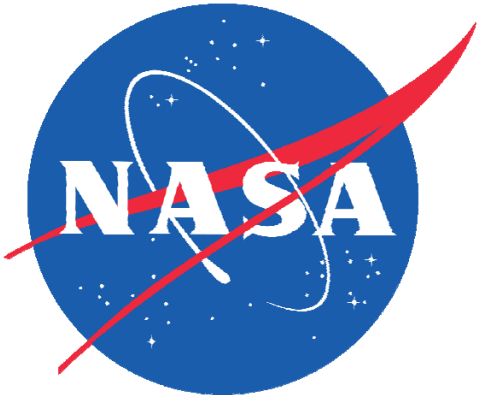
Client

```
from geometry import Point, Geometry
import zmq


addr = 'tcp://localhost:49152'
ctx  = zmq.Context()
cli  = Geometry.Client(ctx, addr, zmq.REQ)

p = Point(1.2, 3.4)
q = Point(5.6, 7.8)
c = cli.centroid([p, q])
d = cli.distance(p, q)

cli.close()
ctx.destroy()
```

Developer can focus on the business logic

Future Directions

- Expand type support in Fortran
- Develop better documentation
- Optimize for performance
- Support more programming languages
- Asynchronous ”futures” model



MAST & YAMSS
Structural Solvers

MAST

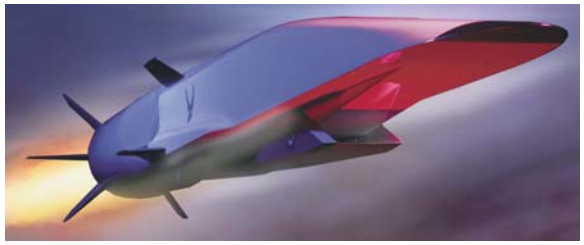
Multidisciplinary Design, Adaptation, & Sensitivity Toolkit

- Elasticity, heat transfer, & compressible flow
- Adjoint solver for sensitivity analysis
- High-order finite elements
- Feature-based and goal-oriented adaptation
- MPI- and thread-based parallelism

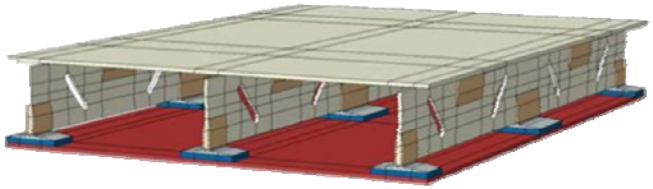
Structures

- Buckling, modal, steady, & transient problems
- Linear and nonlinear elements
- Geometric and material nonlinearities
- Can solve linear analysis about nonlinear point

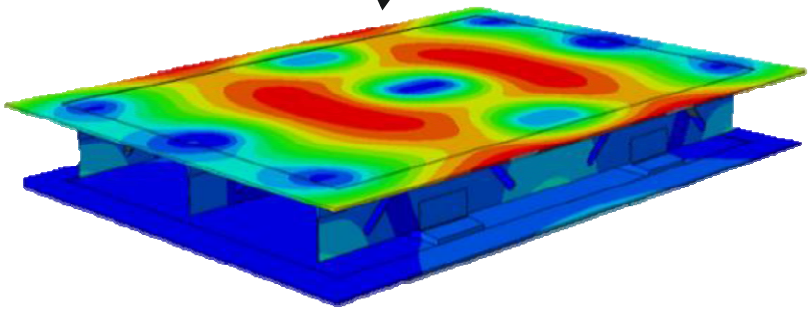
Example Application



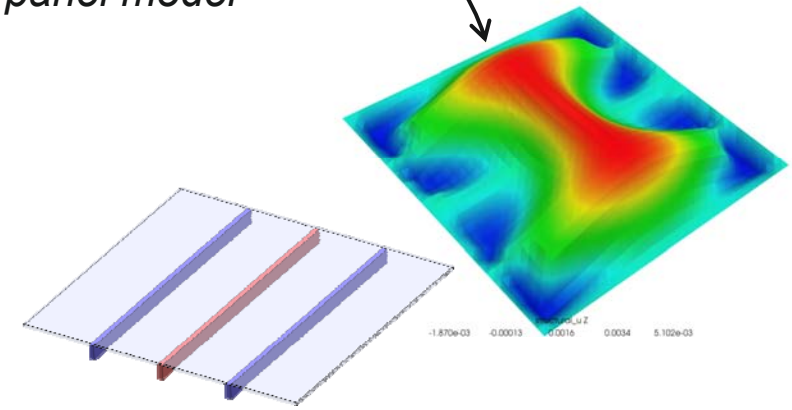
Boeing X-51



hypersonic aircraft panel model

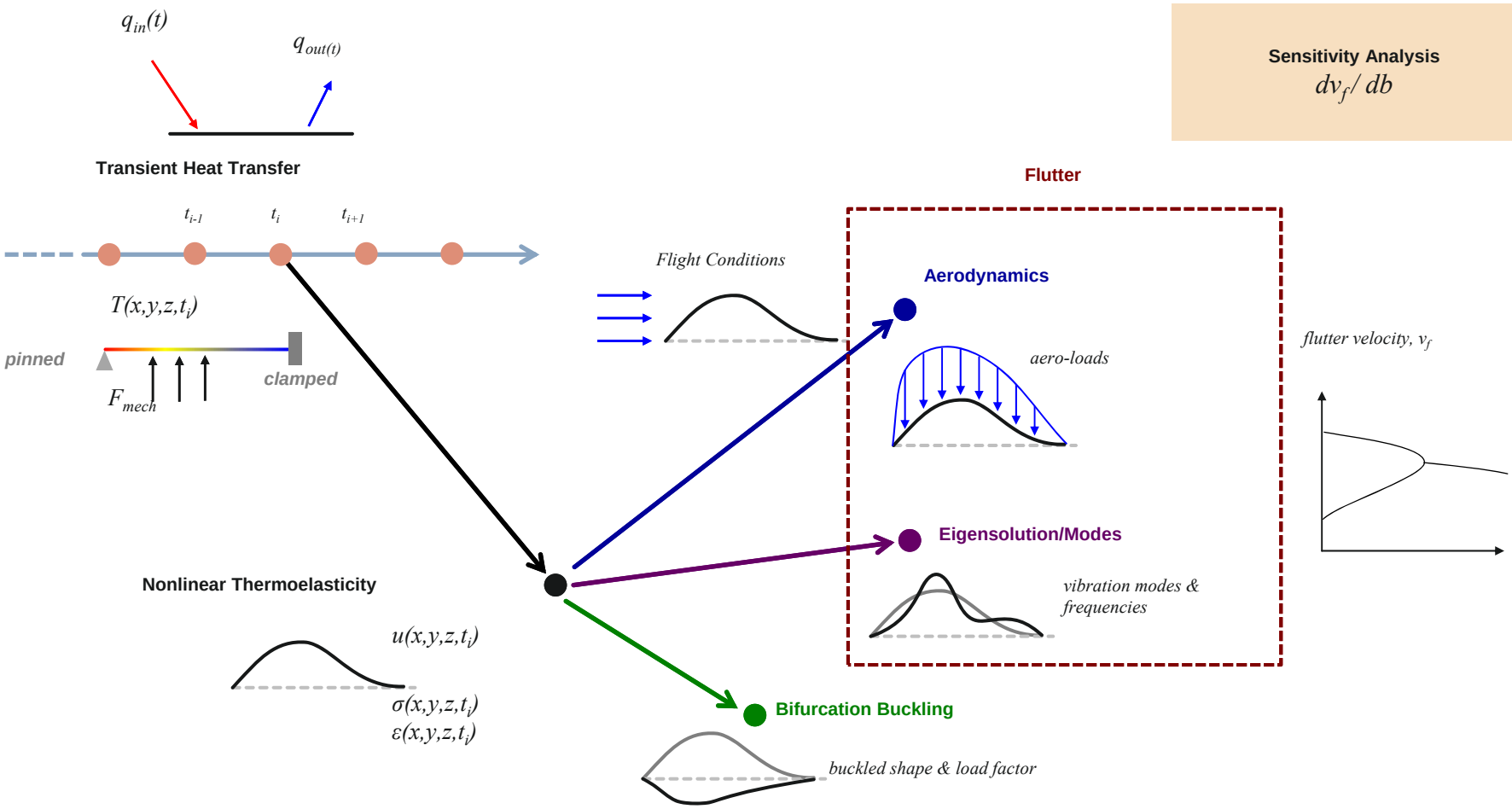


transient nonlinear thermoelasticity



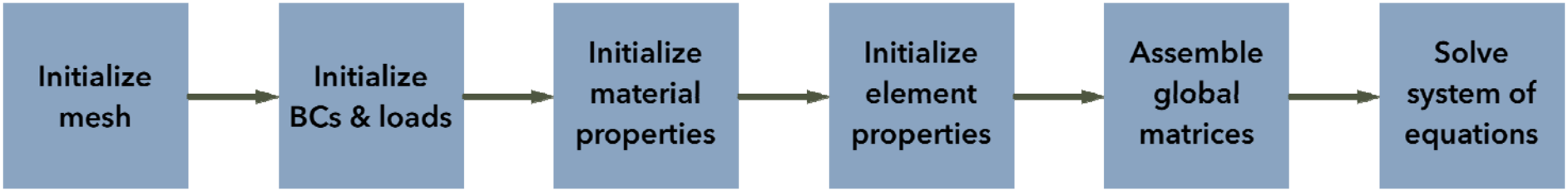
panel design for transonic flutter about nonlinear equilibrium

Analyze Across Disciplines



Solution Process

- MAST is a C++ programming library
- Steps to solve a problem:



- Currently requires writing a C++ program
- Versatile but complex approach
- Working on simpler interface for SAMS

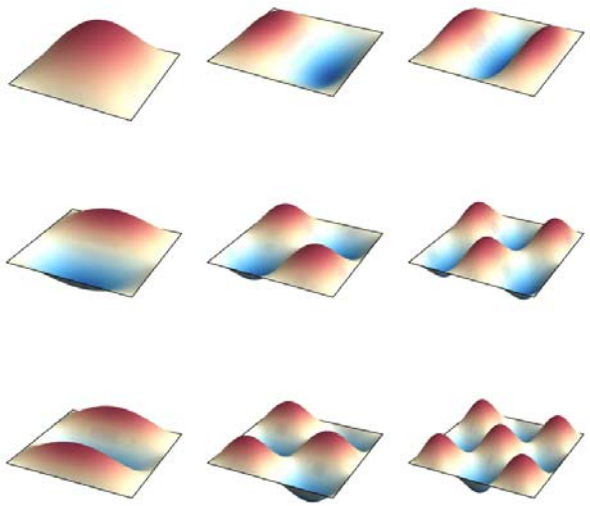
Integration with SAMS

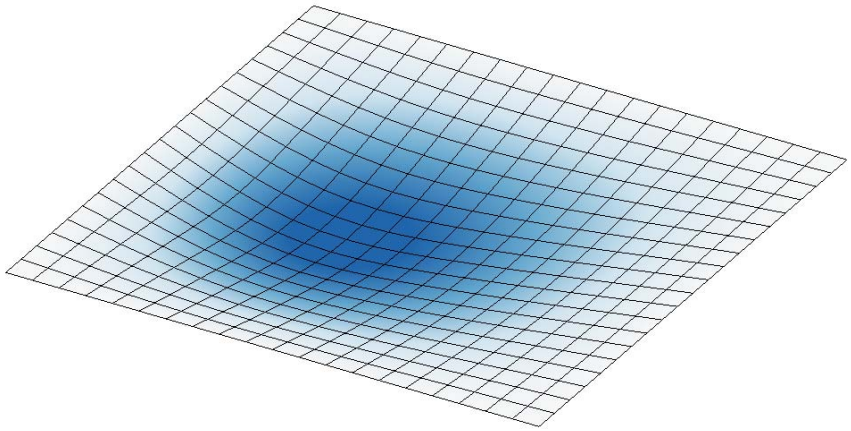
- Time-accurate fluid-structure interaction
- Multidisciplinary adjoint sensitivities
- Streamlined problem definition and execution
- Interface with geometry definition

YAMSS

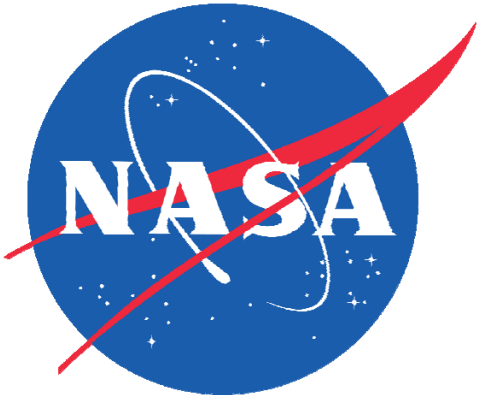
Yet Another Mode-based Structural Solver

- Alternative to FUN3D modal solver
- Use to test modularity of structural solver





simply supported plate w/ sinusoidal forcing



Test Cases

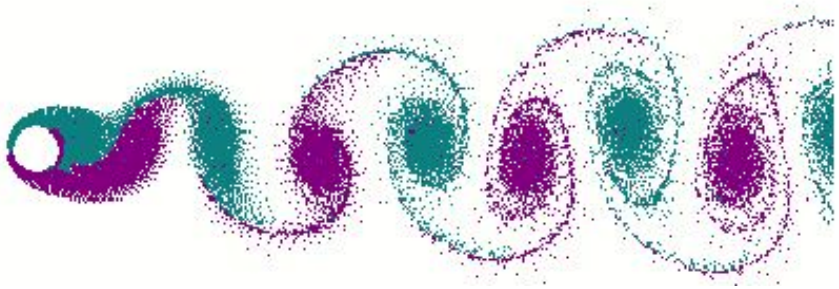
Overview

Case	*n*D	Flow	Structure
Vortex-induced vibrations	2D	transient	spring
Airfoil with gust	2D	transient	linear beams
Turek-Hron	2D	transient	hyperelastic flag
AGARD 445.6	3D	steady	linear modes
G-Wing	3D	transient	aluminum plate
X-56A	3D	steady	built-up structure
Tailless supersonic aircraft	3D	transient	rigid

Incrementally demonstrate capability

Vortex-Induced Vibrations

- Cylinder in cross flow, free to translate or rotate
- Vortical flow may induce vibrations in cylinder
- Parameters: *k*, *Re*



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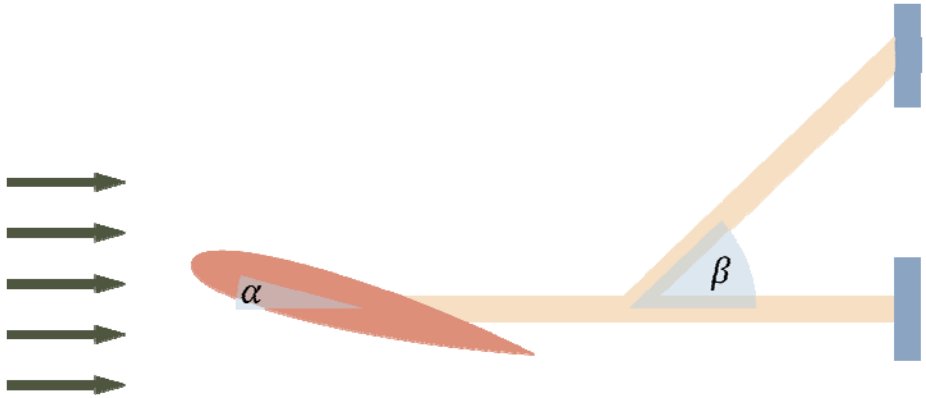
Williamson, C. H. K., and R. Govordhan, “Vortex-induced vibrations.” *Annual Review of Fluid Mechanics* 36 (2004): 413—455.

Airfoil in a Gust

- Sting-mounted airfoil in a transient gust
- Parameters: $U_{g,max}$, α, β, E



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Cross, D. M., Local continuum sensitivity method for shape design derivatives using spatial gradient reconstruction. Diss. Virginia Polytechnic Institute and State University, 2014.

Turek-Hron

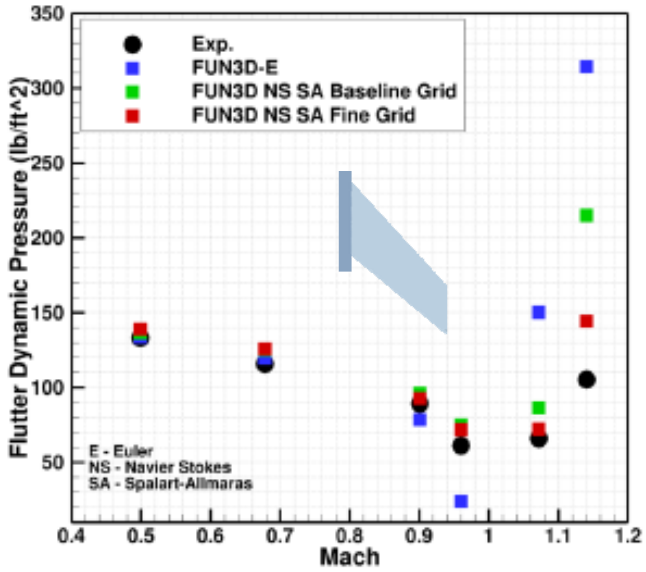
- Rigid cylinder with an attached elastic structure
- Flow induces deformation in elastic structure
- Parameters: Re, U, ρ, E, μ

Reference

Turek, S., and J. Hron, Proposal for numerical benchmarking of fluid-structure interaction between an elastic object and laminar incompressible flow." *Fluid-structure interaction*. Springer Berlin Heidelberg, 2006, 371—385.

AGARD 445.6 Wing

- Standard aeroelastic benchmark problem
- Modal structure
- Parameters: M_∞ , p_∞



Silva et al., *AIAA*, 2014-0496

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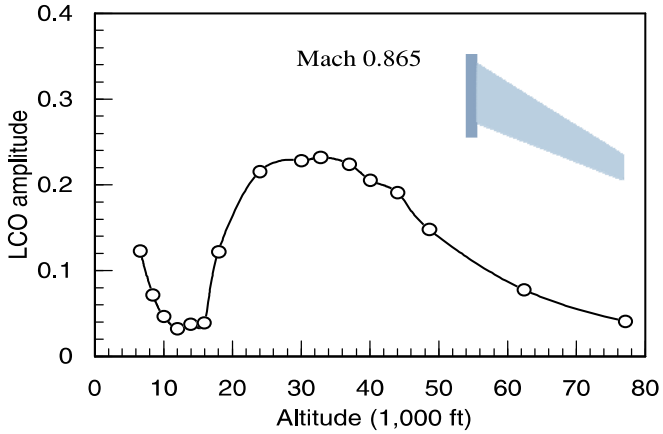
Yates, Jr, E. C., "AGARD standard aeroelastic configurations for dynamic response. Candidate configuration I.-Wing 445.6." NASA TM 100492 (1987).

Lee-Rausch, E. M., and J. T. Batina, "Calculation of AGARD wing 445.6 flutter using Navier-Stokes aerodynamics." AIAA-1993-3476, *11th Applied Aerodynamics Conference* (1993): 9—11.

G-Wing

- Swept transport wing
- Nonlinear structure, exhibits high-altitude LCO
- Parameters: M_∞ , h, E



Bendiksen, *J of Aircraft 46.1*

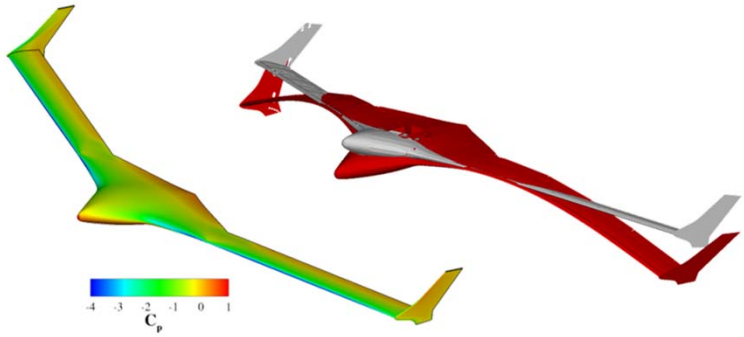
Reference

Bendiksen, O. O. “Transonic limit cycle flutter of high-aspect-ratio swept wings.” *Journal of Aircraft* 45.5 (2008): 1522—1533.

Bendiksen, O. O. “High-altitude limit cycle flutter of transonic wings.” *Journal of Aircraft* 46.1 (2009): 123—136.

X-56A

- Flight-tested UAV with rigid and flexible wings
- Flutter suppression & gust load alleviation
- Parameters: M_∞ , p_∞, K



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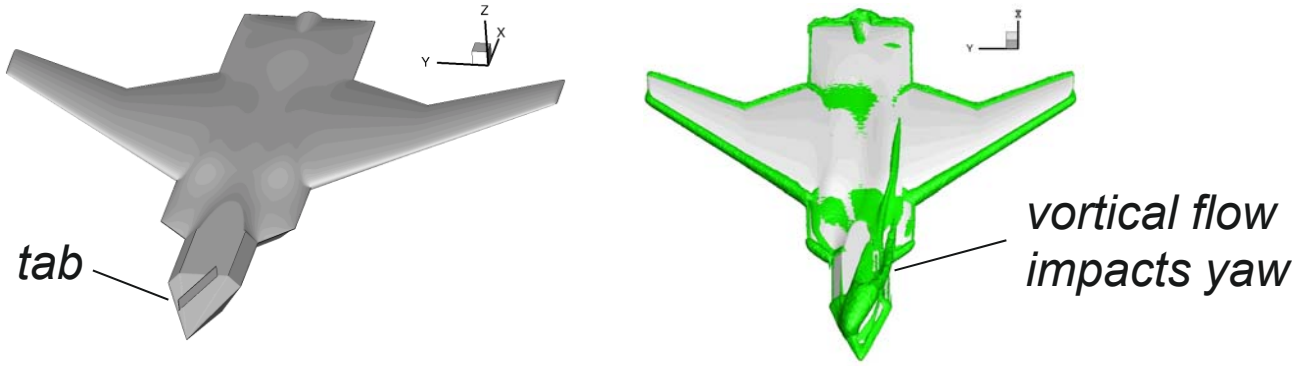
Jones, J., and C. E. Cesnik. “Nonlinear aeroelastic analysis of the X-56 multi-utility demonstrator.” AIAA-2016-1799. *15th Dynamics Specialists Conference*, 2016.

Tailless Aircraft

- Tailless supersonic aircraft
- Fuselage-mounted tabs improve yaw control
- Parameters: *tab shape and position*



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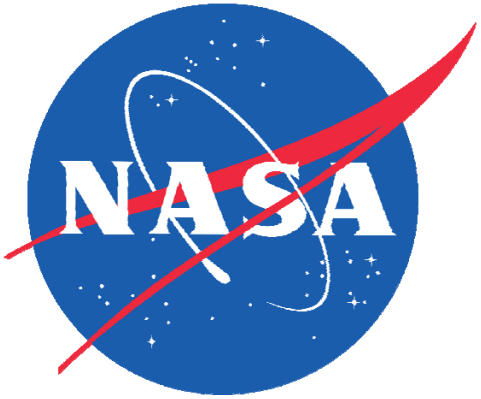

Concluding Remarks

Progress

- Major changes to FUN3D are underway
- MAST improvements are readying it for SAMS
- Integration infrastructure ready for use
- Adopting FUNtoFEM (Georgia Tech) for FSI

Next step: mode-based static aeroelasticity

Personnel

- SAMS has been understaffed
- AFRL has had two unfilled contractor positions
  1. Filled in November
  2. Currently reviewing applicants
- NASA had one unfilled position
  1. Filled in October

Behind schedule, but pace accelerating

Digital Collaboration

- Need to exchange source code and data files
- Existing ”solutions” not working
  - AFRL unsuccessful getting full access to LaRC GitLab
  - NASA unsuccessful getting accounts to AFRL ELSZ
- Large file transfer mechanisms do work
  - But not good for collaboration

Digital collaboration remains a significant problem